

Recent developments in chiral dynamics of hadrons and hadrons in nuclei

E. OSET^{1,*}, M. DORING¹, M. KASKULOV¹, L. ROCA¹, S. SARKAR¹, D. STROTTMAN¹, M.J. VICENTE VACAS¹, V.K. MAGAS², A. RAMOS², AND E. HERNANDEZ³

¹ *Departamento de Física Teórica and IFIC, Centro Mixto, Institutos de Investigación de Paterna - Universidad de Valencia-CSIC*

² *Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, Diagonal 647, 08028 Barcelona, Spain*

³ *Grupo de Física Nuclear, Departamento de Física Fundamental e IUFFyM, Facultad de Ciencias, Universidad de Salamanca,*

In this talk I present recent developments in the field of hadronic physics and hadrons in the nuclear medium. I review the unitary chiral approach to meson baryon interaction and address the topics of the two dynamically generated $\Lambda(1405)$ resonances, with experiments testing it, the $\Lambda(1520)$ and $\Delta(1700)$ resonances, plus the $\Lambda(1520)$, $\Sigma(1385)$ and ω in the nuclear medium.

§1. Introduction

The unitary extrapolations of chiral perturbation theory are having a great impact in hadronic and nuclear physics. They allow one to address the meson meson and meson baryon interactions at low and intermediate energies and have also shown that many known mesonic and baryonic resonances naturally appear as a consequence of these interactions, hence producing dynamically generated states which go beyond the usual $q\bar{q}$ or qqq nature of the mesons and baryons. The identification of such resonances and the study of their properties and their influence in different reactions is a growing field allowing to interpret many phenomena and making predictions on observables of the resonances and special features in reaction dynamics. The main ideas behind this chiral unitary theory are reviewed in.¹⁾ A more recent review on applications to physical processes can also be found in.²⁾

§2. Chiral unitary approach

Although much work has been done along these lines, we follow here the basic ideas of the N/D method, adapted for the meson meson interaction using chiral dynamics in,³⁾ and to the meson baryon case in.⁴⁾ A pedagogical description of the method and applications to physical cases can be seen in.²⁾ The essence of the method consists in the use of the chiral Lagrangians as a source of dynamical interaction, then implement unitarity in coupled channels to get ImT^{-1} from the phase space of the intermediate states of the coupled channels and then implement a

*) e-mail address: oset@ific.uv.es

dispersion relation to get the real part, to which V^{-1} is added, with V the tree level amplitude obtained from the chiral Lagrangians. The method requires a subtraction constant in the dispersion relation and one has an idea of its order of magnitude for it to have a natural size. Applications to the interaction of $\bar{K}N$ and coupled channels is discussed in,²⁾ together with the K^- -nuclear system and other systems and reactions. We take advantage here to present a qualitative description of the method followed to study the interaction of the octet of pseudoscalar mesons with the decuplet of baryons, as done in⁵⁾ and⁶⁾

The lowest order term of the chiral Lagrangian relevant for the interaction of the baryon decuplet with the octet of pseudoscalar mesons is given by.⁷⁾

$$\mathcal{L} = -i\bar{T}^\mu \not{D} T_\mu \quad (2.1)$$

where T_{abc}^μ is the spin decuplet field and D^μ the covariant derivative given in⁶⁾ The formalism provides the identification of the $SU(3)$ component of T to the physical states: $T^{111} = \Delta^{++}$, $T^{112} = \frac{1}{\sqrt{3}}\Delta^+$, $T^{122} = \frac{1}{\sqrt{3}}\Delta^0$, $T^{222} = \Delta^-$, $T^{113} = \frac{1}{\sqrt{3}}\Sigma^{*+}$, $T^{123} = \frac{1}{\sqrt{6}}\Sigma^{*0}$, $T^{223} = \frac{1}{\sqrt{3}}\Sigma^{*-}$, $T^{133} = \frac{1}{\sqrt{3}}\Xi^{*0}$, $T^{233} = \frac{1}{\sqrt{3}}\Xi^{*-}$, $T^{333} = \Omega^-$.

From this Lagrangian, for a meson of incoming (outgoing) momenta $k(k')$ one obtains the simple form for the S -wave transition amplitudes

$$V_{ij} = -\frac{1}{4f^2}C_{ij}(k^0 + k'^0). \quad (2.2)$$

The coefficients C_{ij} for reactions with all possible values of strangeness (S) and charge (Q) are given in Appendix-I and II of.⁶⁾ We then consider $S = -1$ in $I = 0$. In this case there are the $\Sigma^*\pi$ and Ξ^*K states in the coupled channels states. The coefficients are given in⁶⁾ and the interaction is found attractive, leading to a resonance which can be identified with the $\Lambda(1520)$ and would be essentially a bound state of the $\Sigma^*\pi$.

The results of the $|T|^2$ are shown in.⁶⁾ There one can see peaks which can be associated to different resonances. Here in this talk I will only discuss the $\Lambda(1520)$ and the $\Delta(1700)$.

§3. The two $\Lambda(1405)$ states dynamically generated

We come back to the interaction of the octet of pseudoscalar mesons with the octet of baryons and refer to the work⁸⁾ where two $\Lambda(1405)$ states were found. In an $SU(3)$ symmetric world the combination of 8×8 representation gives rise to the irreducible representations: 1, 8_s , 8_a , 10, $\bar{10}$ and 27. The chiral Lagrangians (lowest order chiral Lagrangian) that we use are $SU(3)$ symmetric and only the different masses of the hadrons break this symmetry after unitarization. If we do an $SU(3)$ symmetric approximation, making the masses of the baryons equal and the masses of the mesons equal, and look for poles of the scattering matrix, we find poles corresponding to the octets, which are degenerate in this limit, and the singlet.

By using the physical masses of the baryons and the mesons, the position of the poles change and the two octets split apart in four branches, two for $I = 0$ and two

for $I = 1$, as one can see in,⁸⁾ which we reproduce in Fig. 1. In the figure we show the trajectories of the poles as a function of a parameter x that breaks gradually the SU(3) symmetry up to the physical values.

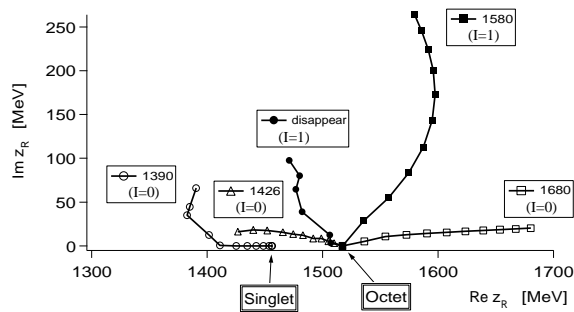


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octet. The symbols correspond to the step size $\delta x = 0.1$.

The splitting of the two $I = 0$ octet states is very interesting. One moves to higher energies to merge with the $\Lambda(1670)$ resonance and the other one moves to lower energies to create a pole, quite well identified below the $\bar{K}N$ threshold, with a narrow width. On the other hand, the singlet also evolves to produce a pole at low energies with a quite large width.

We note that the singlet and the $I = 0$ octet states appear nearby in energy and what experiments actually see is a combination of the effect of these two resonances. We should also note that the narrow state at higher energy couples mostly to $\bar{K}N$ and the wide one at lower energies couples mostly to $\pi\Sigma$. Recent works^{11)–14)} include contributions from higher order Lagrangians and they also have the narrow pole very similar to,⁸⁾ the wide pole also appearing at lower energies than the narrow one, but there is some dispersion in the actual values of the width. The results for the amplitudes obtained with the lowest order Lagrangian⁸⁾ fall within the theoretical uncertainties of the more complete models.¹⁴⁾

The recently measured reaction $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ ⁹⁾ allows us to test already the two-pole nature of the $\Lambda(1405)$. This process shows a strong similarity with the reaction $K^-p \rightarrow \gamma\Lambda(1405)$, where the photon is replaced by a π^0 , and which was studied in.¹⁰⁾ Our model¹⁵⁾ for the reaction $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ in the energy region of $p_{K^-} = 514$ to 750 MeV/c, as in the experiment,⁹⁾ considers those mechanisms in which a π^0 loses the necessary energy to allow the remaining $\pi^0\Sigma^0$ pair to be on top of the $\Lambda(1405)$ resonance. The most important mechanisms is given by the diagram of Fig. 2. As a consequence, the $\Lambda(1405)$ thus obtained comes mainly from the $K^-p \rightarrow \pi^0\Sigma^0$ amplitude which, as mentioned above, gives the largest possible weight to the second (narrower) state.

We recall that the shape of the $\Lambda(1405)$ in the $\pi^-p \rightarrow K^0\pi\Sigma$ reaction was shown in Ref.¹⁶⁾ to be largely built from the $\pi\Sigma \rightarrow \pi\Sigma$ amplitude, which is dominated by the wider, lower energy state. In Fig. 2 we show the experimental results for both experiments, showing a quite different shape in consonance with the theoretical

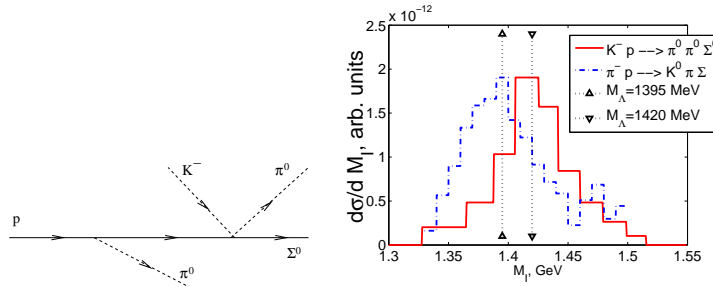


Fig. 2. Left: Nucleon pole term for the $K^- p \rightarrow \pi^0 \pi^0 \Sigma$ reaction. Right: Two experimental shapes of $\Lambda(1405)$ resonance. See text for more details.

findings of¹⁶⁾ and¹⁵⁾ The quite different shapes of the $\Lambda(1405)$ resonance seen in these experiments can be interpreted in favour of the existence of two poles with the corresponding states having the characteristics predicted by the chiral theoretical calculations.

It is interesting to see that a similar shape for the $\Lambda(1405)$ was seen some time ago in the reaction $K^- p \rightarrow \gamma \pi \Sigma$.¹⁰⁾ In this respect it would be interesting to carry out this reaction experimentally. We also have here the suggestion for further reactions which could provide extra evidence on this issue. These would be the reactions:

$K^- p \rightarrow \pi^0 \gamma \Lambda$ and $\pi^- p \rightarrow K^0 \gamma \Lambda$ looking for the $(\gamma \Lambda)$ invariant mass, plus the $K^- p \rightarrow \pi^0 \gamma \Sigma^0$ and $\pi^- p \rightarrow K^0 \gamma \Sigma^0$ looking for the $(\gamma \Sigma)$ invariant mass.

This would provide the radiative decay of the $\Lambda(1405)$ into $\gamma \Lambda$ and $\gamma \Sigma^0$ with the likely result of finding different rates depending on the reaction because of the two $\Lambda(1405)$ states.

§4. The $\Lambda(1520)$

As we have seen in section 2, the channels $\pi \Sigma(1385)$ and $K \Xi$ form the basis for the $S = -1$ and $I = 0$. The interaction in this sector is attractive and a resonance pole appears which can be brought close to the $\Lambda(1520)$ mass with fine tuning of the subtraction constants in the dispersion relation. Yet, with these channels and the position of the resonance at the experimental mass, the resonance would not have a width and would qualify as a bound state of the $\pi \Sigma(1385)$. This is of course rough and one should include the $\bar{K} N$ and $\pi \Sigma$ channels which appear in D-wave and which provide the main source of decay of the $\Lambda(1520)$. The inclusion of the D-wave channels is done in.^{17),18)} There the couplings provided by the chiral Lagrangian between the $\pi \Sigma(1385)$ and $K \Xi$ states is kept and the couplings to the D-wave states are fitted to experimental amplitudes. The complete model shows that the coupling of the $\Lambda(1520)$ to the $\pi \Sigma(1385)$ state is still the largest, and thus the realistic world still keeps some memory of the simplified one with only the s-wave channels. The complete models allow us to address several reactions discussed in.^{17),18)} In Fig. 4 we show our results for $K^- p \rightarrow \pi^0 \pi^0 \Lambda$ and $K^- p \rightarrow \pi^+ \pi^- \Lambda$ cross section respectively along with experimental data from Refs.^{19),20)} The dashed line represents the contribution from mechanisms other than the unitarized coupled channels, (a) and (b) of Fig. 3 and the solid one gives the coherent sum of all the processes, which includes

the amplitude of the left in Fig. 3, where the chiral dynamics of the $\bar{K}N \rightarrow \pi\Sigma^*$ transition appears. Note that the cross section of the $K^-p \rightarrow \pi^+\pi^-\Lambda$ reaction is a factor two larger at the peak than the $K^-p \rightarrow \pi^0\pi^0\Lambda$ one. Hence, the agreement with the data is a non-trivial accomplishment of the theory since the $\bar{K}N \rightarrow \pi\Sigma^*$ amplitude has not been included in the fit. It would be interesting to measure the reaction of¹⁹⁾ at lower energies to get the $\Lambda(1520)$ peak, something possible at JPARC.

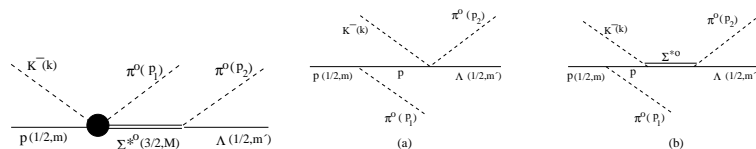


Fig. 3. Scheme for $K^-p \rightarrow \pi^0\Sigma^*(1385) \rightarrow \pi^0\pi^0\Lambda$. The blob indicates the unitarized vertex. Last two diagrams for conventional background

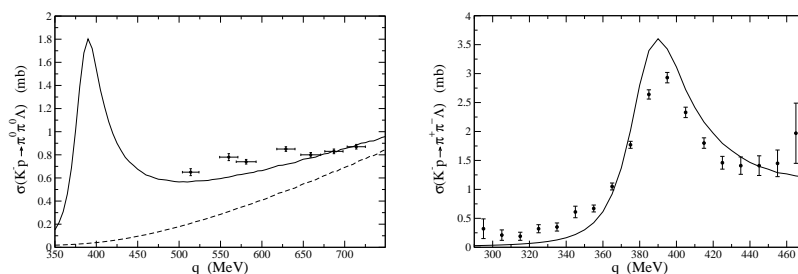


Fig. 4. Result for the $K^-p \rightarrow \pi^0\pi^0\Lambda$ cross section. Experimental data from Ref.¹⁹⁾

Other issues related to the $\Lambda(1520)$ which have also been addressed within the chiral unitary approach are the coupling of the K^* to the resonance and the radiative decay. The first topic is addressed in²¹⁾ and the coupling is compared to that obtained from ordinary quark models. The second topic is addressed in,²²⁾ where one finds that the radiative decay of the $\Lambda(1520)$ to $\Sigma\gamma$ is well reproduced, but the one to $\Sigma^*\gamma$ is quite short of the experimental results. This magnitude becomes a good test of possible extra components of the $\Lambda(1520)$, like some 3q components. Comparison of the results with quark model results,²³⁾ and some evaluations done in,²²⁾ lets one conclude that a small fraction of a 3q component, packed like in the chiral quark models, in addition to the meson cloud component of the dynamically generated state, could bring the results in agreement with data, but more work is needed there.

§5. The $\Delta(1700)$ resonance

The $\Delta(1700)$ is another of the resonances coming from the interaction of the octet of mesons with the baryon decuplet. The results for the different channels, as studied in²⁴⁾ and²⁵⁾ are by no means trivial. Should we assume that the $\Delta(1700)$ belongs to an SU(3) decuplet, as suggested in the PDG, it is easy to see, using SU(3) Clebsch Gordan coefficients, that the couplings to the $\Delta\pi$, Σ^*K and $\Delta\eta$ states in

$I = 3/2$ would be proportional to 1, 2/5, 1/5. However, with the dynamically generated $\Delta(1700)$ they are proportional to 1, 11.56 and 4.84 respectively. Hence, one assumption or the other lead to differences in the cross sections of the order of a factor 400-900 depending on the channel. This said, the agreement found in,²⁵⁾ within theoretical and experimental uncertainties, with the data for photon and pion induced reactions having the $\Delta(1700)$ in the entrance channel, must be considered a real success. Below we plot some results. In addition there are recent preliminary data for these reactions at ELSA, with smaller errors, from F. Klein et al. for the reactions of the first figure, and from M. Navova et al. for the other two reactions which fall within the shaded region of our calculations. The theoretical band comes from uncertainties in input from the PDG used, which could be reduced in the future with improvements in the measurements of some partial decay widths.

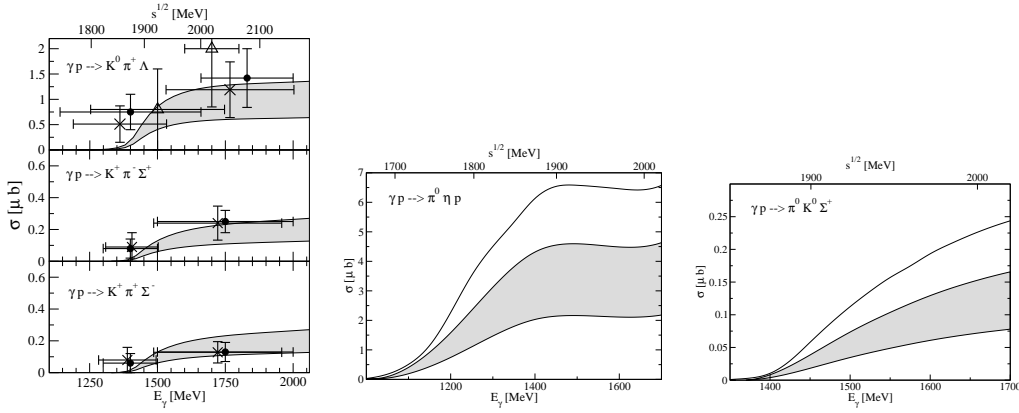


Fig. 5. Photoproduction of strange and η particles. The gray bands are the results of.²⁵⁾

§6. $\Lambda(1520)$ and $\Sigma(1385)$ in the nuclear medium

The coupling of the $\Lambda(1520)$ to the $\pi\Sigma^*$ state is very large but the decay is practically suppressed because there is no phase space for the decay, up to a small overlap considering the width of the resonances. However, when we consider the decay in the medium, the pion can excite a ph with energy starting from zero, and then one gains 140 MeV of phase space for the decay, see Fig. 6. This reminds one of the situation with the mesonic and nonmesonic decay of the Λ in a nucleus, in Λ hypernuclei, where the mesonic decay is essentially forbidden by Pauli blocking and then the ph excitation of the pion gives rise to the nonmesonic decay, which is dominant in the nucleus. The calculations have been done in²⁶⁾ and the modifications to the $\Lambda(1520)$ width coming from the $\pi\Sigma$ and $\bar{K}N$ in the nuclear medium are also taken into account. In that work the selfenergy of the $\Sigma(1385)$ is also evaluated and used to calculate the selfenergy of the $\Lambda(1520)$. One finds a substantial increase in the width of the $\Sigma(1385)$, of more than a factor two for nuclear matter density, and a small shift of the mass. These results are consistent with another independent and quite different evaluation of the $\Sigma(1385)$ selfenergy done in,²⁷⁾ where it appears as a

byproduct of the study of the p-wave $\bar{K}N$ interaction in the nuclear medium where the $\Sigma(1385)$ pole term is one of the important ingredients.

In fig. 7 we show results for the $\Lambda(1520)$ width in medium. The figure to the left shows the width as a function of the nuclear density. We can see that at $\rho = \rho_0$ the width is about five times bigger than the free width. This is a spectacular increase which should not go unnoticed in experiments and some suggestions have already been done in.²⁸⁾

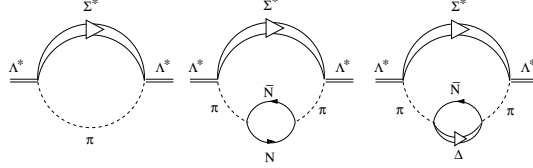


Fig. 6. The renormalization of $\Lambda(1520)$ in the nuclear medium.

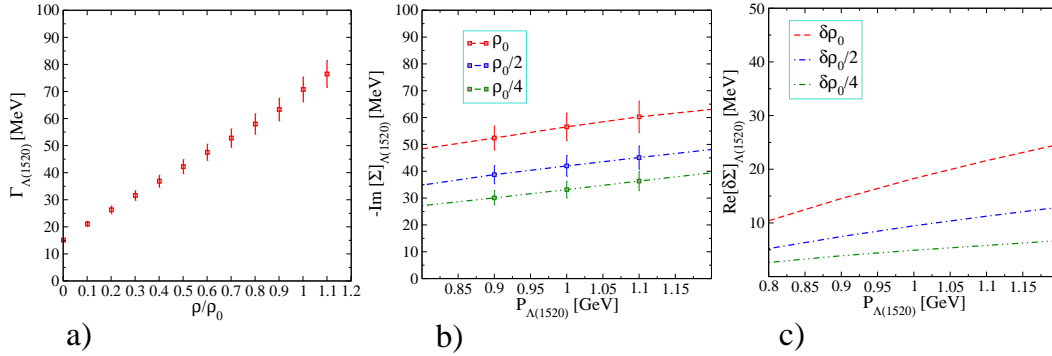


Fig. 7. Values with theoretical uncertainties for the width of the $\Lambda(1520)$ at rest in the medium, including the free width, as function of the nuclear matter density ρ/ρ_0 (a). The imaginary (b) and the vacuum subtracted real (c) parts of the $\Lambda(1520)$ selfenergy as a function of the $\Lambda(1520)$ three momentum.

§7. ω in the nuclear medium

This issue is an interesting one and related to the general topic of the possible mass shift of the vector masses in the nuclear medium predicted by some theories. An interesting experiment was done in²⁹⁾ by means of the $\gamma A \rightarrow \omega(\pi^0\gamma)A'$ reaction, where the ω was identified from the invariant mass of the $\pi^0\gamma$ from its decay into this channel. A shift of the invariant mass with respect to the one in the γp reaction was attributed in²⁹⁾ to a shift of the ω mass in the medium. In Ref.³⁰⁾ a reanalysis of the process is done by means of a Monte Carlo simulation procedure that traces the interaction of all the particles inside the nucleus and considers a possible shift of mass and width of the ω in the nucleus which is fitted to the data. An important novelty of this work is that it chooses the background in the nucleus proportional to the one in the proton reaction in the energy region around the ω mass, while in²⁹⁾ the background is manifestly changed, and increased at higher masses, in such a way

that there are no events in the region of high invariant masses. Hence, the shift to lower ω masses claimed in²⁹⁾ can be directly linked to the choice of background. On the contrary, in³⁰⁾ we find that the data demand a large ω width, of the order of 90 MeV at normal nuclear matter density, but there is no need for a shift of the mass. In Fig. 8 we show the results obtained in³⁰⁾ together with the backgrounds in the nucleus of ^{92}Nb and on the proton (inset). In addition, in³¹⁾ it is found that should the ω potential be sufficiently attractive to support bound ω states in nuclei, one needs a better resolution than the one available at ELSA in²⁹⁾ to see the states in the γA reactions looking for p in coincidence at small angles. These findings, and others discussed in³¹⁾ are very useful to help interpret properly the results obtained in experiments.

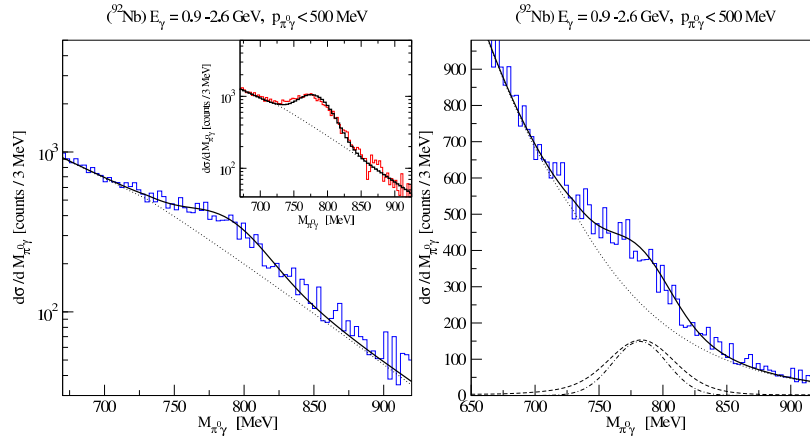


Fig. 8. Background (dotted line) and ω signal in the proton (inset) and the nucleus.

§8. Conclusions

We have presented a selection of recent results on hadron physics and hadrons in the nuclear medium which, once again, show the adequacy of chiral unitary theory to address the world of hadron physics at intermediate energies and subsequent problems of hadrons in a nuclear environment. We could see how some properties of resonances like the $\Lambda(1520)$ and $\Delta(1700)$ can be naturally traced to the interpretation of these resonances as dynamically generated from the interaction of the octet of pseudoscalars with the decuplet of baryons. We also showed some reactions supporting the findings of chiral theory about the existence of two $\Lambda(1405)$ states. We then showed how this nature has immediate repercussions for the behaviour of these resonances in nuclei, as a consequence of which the $\Lambda(1520)$ gets a very large width in the medium, of the order of five times bigger than its free width at normal nuclear matter density. Finally we also presented some results of a reanalysis of the results of ω production in nuclei and found that, contrary to what was assumed from

a previous analysis, a recent work subtracting a more appropriate background, and imposing the constraints of a large width in the medium obtained in the same experiment, showed that the results can be interpreted in terms of this enlarged width without invoking any shift in the mass.

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